A Novel Method of High Accuracy, Wavefront Phase and Amplitude Correction for Coronagraphy

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Abstract

Detection of extra-solar, and especially terrestrial-like planets, using coronagraphy requires an extremely high level of wavefront correction. For example, the study of Woodruff et al. (2002) has shown that phase uniformity of order $10^{-4}\lambda$(rms) must be achieved over the critical range of spatial frequencies to produce the ~10^{10} contrast needed for the Terrestrial Planet Finder (TPF) mission. Correction of wavefront phase errors to this level may be accomplished by using a very high precision deformable mirror (DM). However, not only phase but also amplitude uniformity of the same scale (10^{-4}) and over the same spatial frequency range must be simultaneously obtained to remove all residual speckle in the image plane. We present a design for producing simultaneous wavefront phase and amplitude uniformity to high levels from an input wavefront of lower quality. The design uses a dual Michelson interferometer arrangement incorporating two DMs and a single, fixed mirror (all at pupils) and two beamsplitters: one with unequal (asymmetric) beam splitting and one with symmetric beam splitting. This design allows high precision correction of both phase and amplitude using DMs with relatively coarse steps, and permits a simple correction algorithm.

Summary

- To achieve the contrast to image exo-solar planets using coronnagraphy, both wavefront phase and amplitude need to be uniform to very high levels. For amplitude -
  - "Jupiter-like" contrast of 10^9: intensity uniformity of ~0.36%
  - "Earth-like" contrast of 10^{10}: intensity uniformity of ~0.04%
- Various Michelson interferometer arrangements incorporating multiple deformable mirrors (DM) can be used to reduce wavefront errors of both phase and amplitude. The major performance trade is between the range of phase which can be corrected and the required accuracy and stability of the DMs.
  - A single Michelson, using 2 DMs, can correct a full range of 1λ phase errors but has the highest requirement on DM accuracy to correct to TPF levels.
  - A dual asymmetric Michelson arrangement with 2 DMs, a single fixed mirror, and an asymmetric beamsplitter can achieve TPF level contrast with lower accuracy DMs but over a more restricted range of phase errors (ex. $1/8\lambda$ full range).
  - A dual asymmetric Michelson with 3 DMs, and asymmetric beam splitter can capture a full 1λ phase range and has the lowest requirements on DM accuracy.

The particular system design selected depends on the required range of phase and amplitude necessary to correct and the accuracy and stability of the DM system.

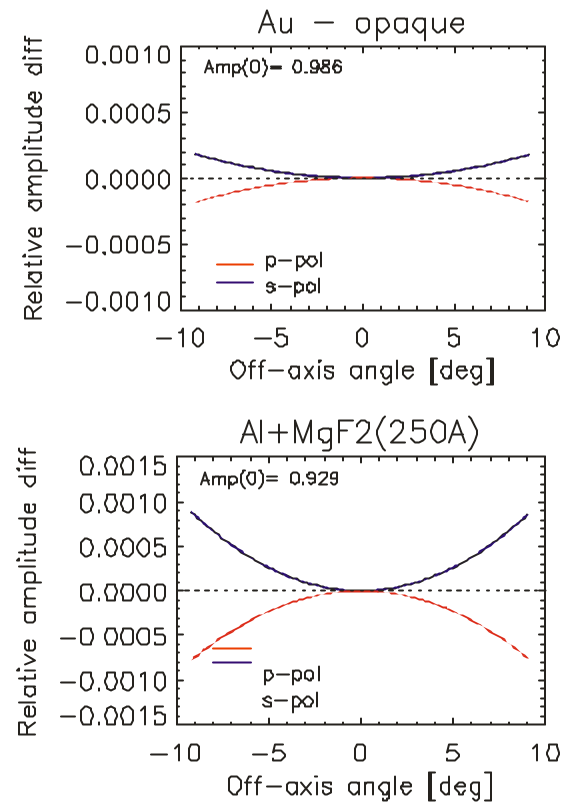
- The current designs have bandpass limitations; variations which are less sensitive to wavelength are being studied.

Introduction

- Detection of earth-like planets by coronagraphy requires extremely high reduction of diffracted & scattered light in the final image ($\sim 10^{-10}$). This sets requirements on <u>phase uniformity</u> ($\sim 10^{-4}\lambda_{rms}$,$\Delta f \sim$4-100 cycles/aperture, Woodruff et al.[1]). Non-uniformity of amplitude will produce similar speckles and comparable <u>amplitude uniformity</u> is also required.
- Amplitude non-uniformity can occur for several reasons:
  - coating effects -
    - variation of reflectance with angle of incidence of mirror coatings (see adjacent figure)
    - variation of coating growth properties with angle of incidence & substrate properties
  - aging
    - contamination
    - pinhole growth
  - scatter variations correlated with substrate surface quality

- We investigate some designs for wavefront correction using various Michelson interferometer configurations. Littman et al.[2], proposed using a Michelson interferometer corrector with spatial light modulators. Here we propose multiple deformable mirror (DM) configurations since DM are a more well developed technology with nearly achromatic performance.

Mirror amplitude reflectance variation with angle of incidence

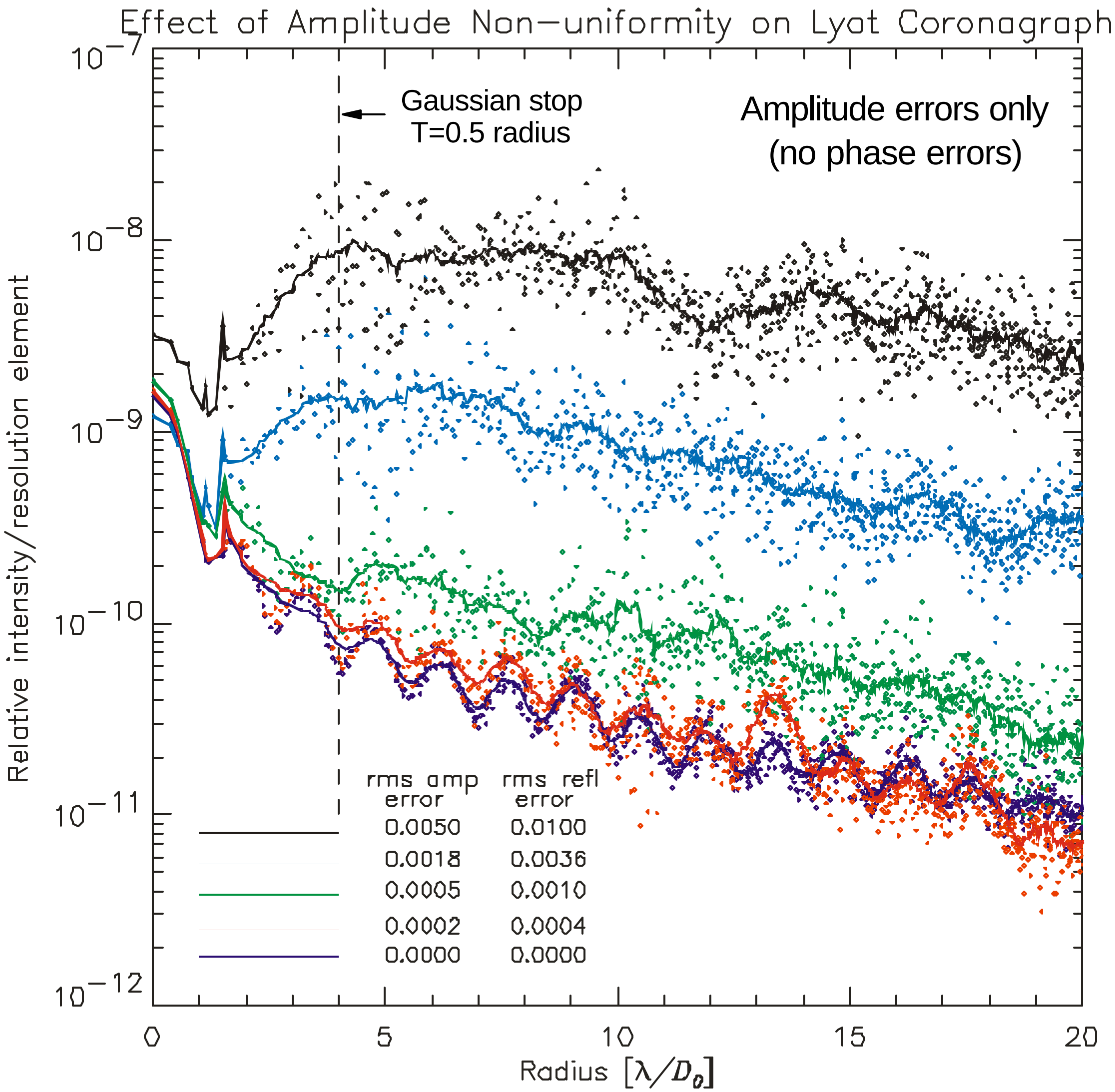


Plots show the variation of reflected amplitude from a single f/1.5 mirror (example primary mirror) at 780nm for opaque gold (upper panel) and Al+MgF_2 (lower panel).

(1) Woodruff, R., Ridgeway, S., Lyon, R., Burrows, C. , Gezari, D., Harwit, M., Melnick, G., Nisenson, P., Spergel, D., Kaylor, L., Peterson, L., Friedman, E., Kaplan, M., "Feasibility of and Technology Roadmap for Coronagraphic Approaches to TPF", NASA NRA 01-OSS-04, Extra-Solar Planets Advanced Mission Concepts, Type 3 Study, 2002.

(2) M.G. Littmann, M. Carr, J. Kasdin, R. Vanderbei, D. Spergel, American Astronomical Society Meeting, poster 19.03, Jan 2003,

The Effect of Non-uniform Amplitude On A Lyot Coronagraph



We modeled the effect of various levels of amplitude only errors (no phase errors) on a Lyot coronagraph with a Gaussian, soft stop.

Coronagraph parameters

- Lyot
- Gaussian soft stop, $T_{1/2}$ point at 4λ/D
- Lyot stop radius =0.72

Input Wavefront Error Distribution

Amplitude error distribution:

PSD $\propto 1/f^2$

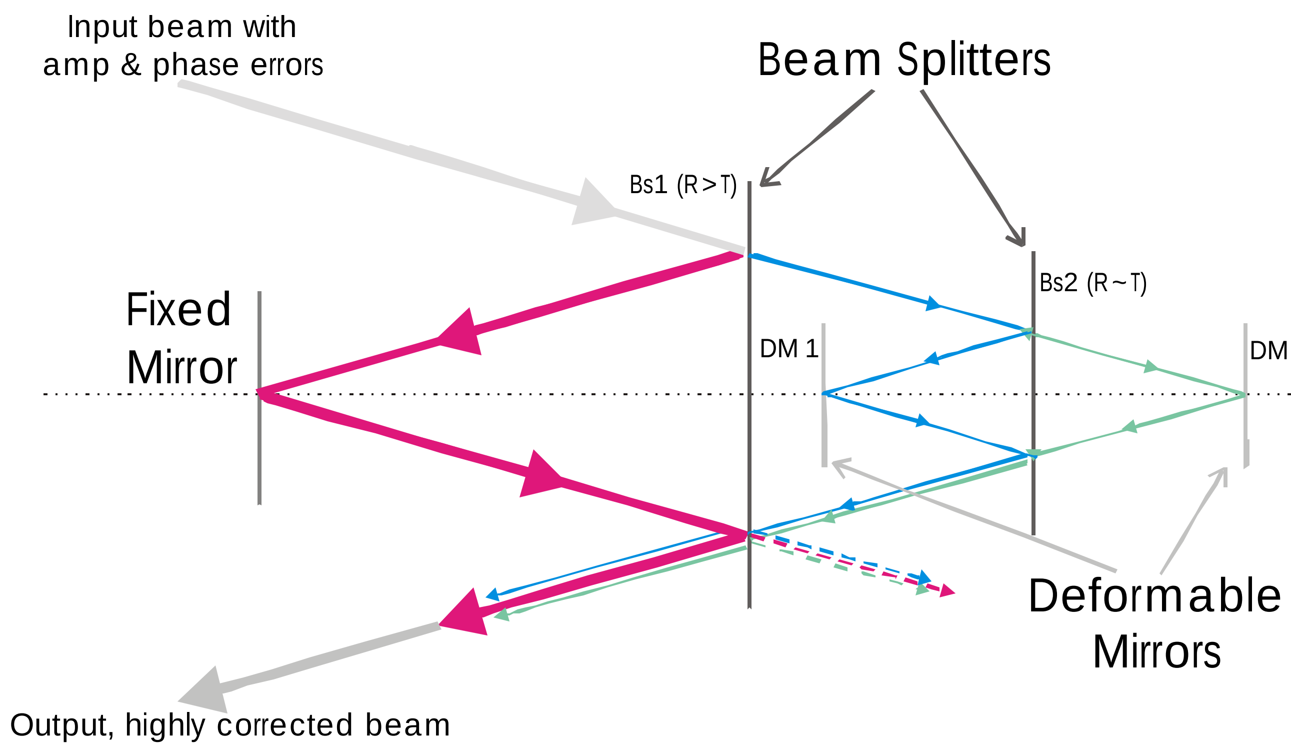
bandwidth: 1-64 cycles/aperture

rms level: as shown

- "Jupiter-like" contrast of 10^9 requires amplitude uniformity of $\leq 1.8\times10^{-3}$ rms (0.36% rms intensity uniformity)
- "Earth-like" contrast of 10^{10} requires amplitude uniformity of $\leq 2.0\times10^{-4}$ rms (0.04%rms intensity uniformity)

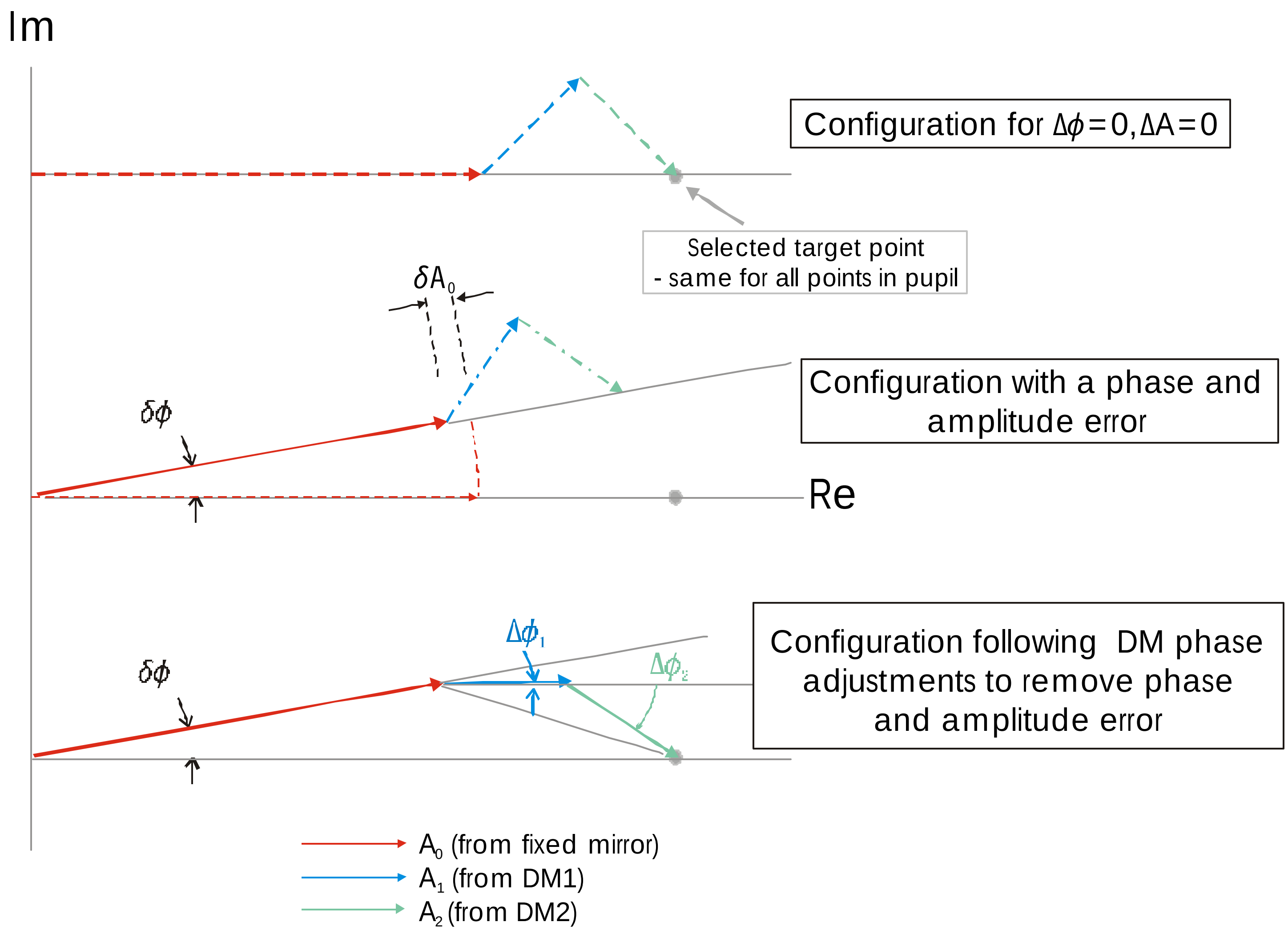
Asymmetric Dual Michelson Corrector

- We assume the input wavefront is "pretty good" and the goal is to "clean it" or improve the uniformity to ~10^{-4}.
- We separate out a small portion of the beam, alter it's phase & amplitude and recombine it with the main beam to produce a highly corrected wavefront, which is passed on to the coronagraph.



The fixed mirror and deformable mirrors (DM1 & DM2) are all located at pupils.

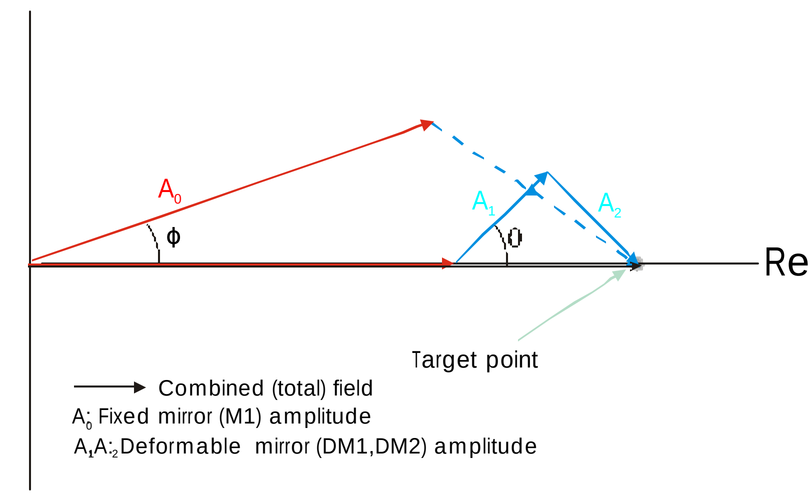
Correction With The Asymmetric Dual Michelson



- Select a "target point" with a specified value of amplitude and phase.
- Adjust the phases of DM1 & DM2 at each point in the beam so the resultant field has the same target amplitude and phase. The wavefront is now corrected over the full beam.

Correction Range & Accuracy

Correction Range



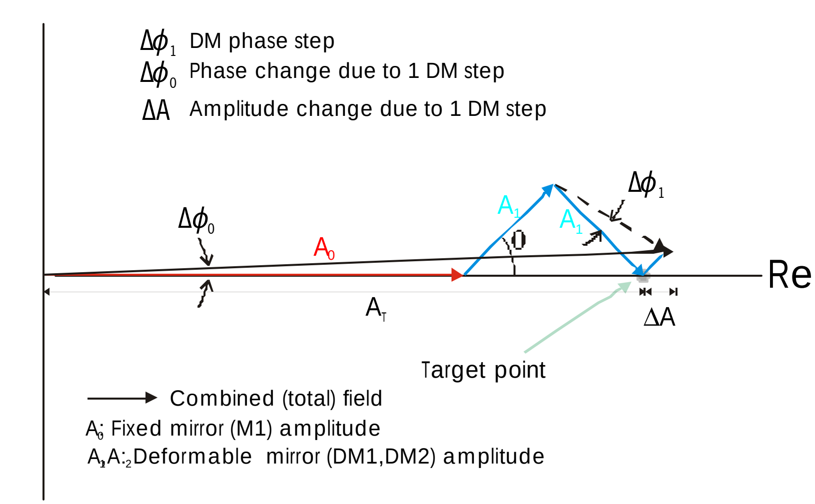
This figure illustrates the range of correctable phase (2f) for a given ratio of amplitudes (DM/fixed mirror components)

$$\cos(\phi) = 1 - \frac{2\left(\frac{A_1}{A_0}\right)^2 \sin^2(\theta)}{1+2\left(\frac{A_1}{A_0}\right)\cos(\theta)}$$

The phase correction range of the asymmetric dual Michelson is limited by the ratio of amplitudes in the DM arm (A_1,A_2) to the fixed mirror arm (A_0) as set by the asymmetric beamsplitter. Smaller DM amplitudes (greater asymmetry) results in a more restricted phase correction range.

Step Size & Resolution

A single phase step of either DM results in a change of system phase and amplitude.



system phase step size

$$\tan(\Delta\phi_0) = \frac{\left(\frac{A_1}{A_0}\right)\Delta\phi\cos(\theta)}{1+2\left(\frac{A_1}{A_0}\right)\cos(\theta)}$$

system amplitude step size

$$\frac{\Delta A}{A_T} = \frac{\left(\frac{A_1}{A_0}\right)\Delta\phi\sin(\theta)}{1+2\left(\frac{A_1}{A_0}\right)\cos(\theta)}$$

Step Size Limits

	Asymmetric Dual Michelson	Single Symmetric Michelson
	$\frac{A_1}{A_0} \ll 1$	$\frac{A_1}{A_0} \gg 1$
$\Delta\phi_0$[waves]	$\frac{\Delta\phi_1}{2\pi}\boxed{\left(\frac{A_1}{A_0}\right)}\cos(\theta)$	$\frac{1}{2}\left(\frac{\Delta\phi_1}{2\pi}\right)$
$\frac{\Delta A}{A_T}$	$\Delta\phi_1\boxed{\left(\frac{A_1}{A_0}\right)}\sin(\theta)$	$\frac{1}{2}(\Delta\phi_1)\tan(\theta)$

The asymmetric dual Michelson can have significantly greater resolution than a single, symmetric Michelson allowing less precise DMs to be used.

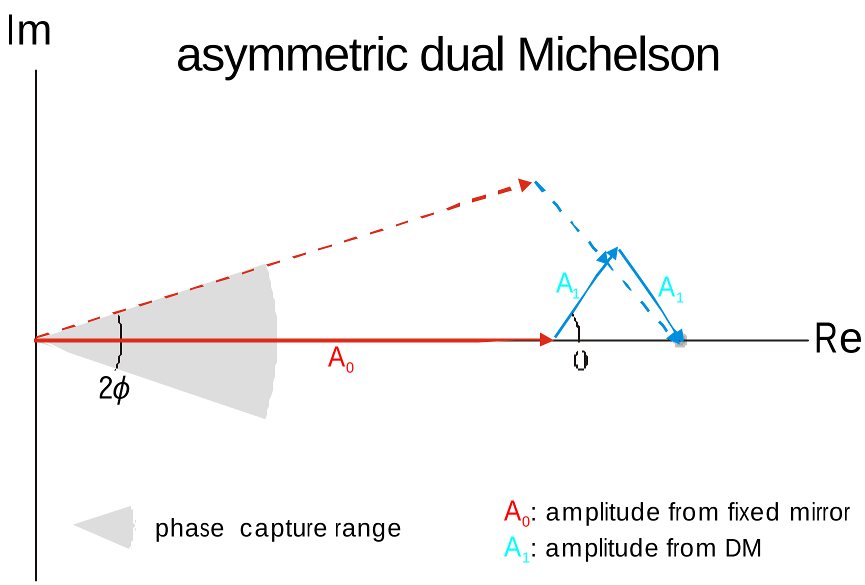
Range of Designs

- The ratio of amplitudes from the fixed and deformable mirrors defines a family of WF correctors, from asymmetric dual to single Michelson systems.
- The properties of beamsplitter 1 can be selected to trade between phase & amplitude range and required accuracy for a given DM step size.

Increased phase & amplitude resolution ←

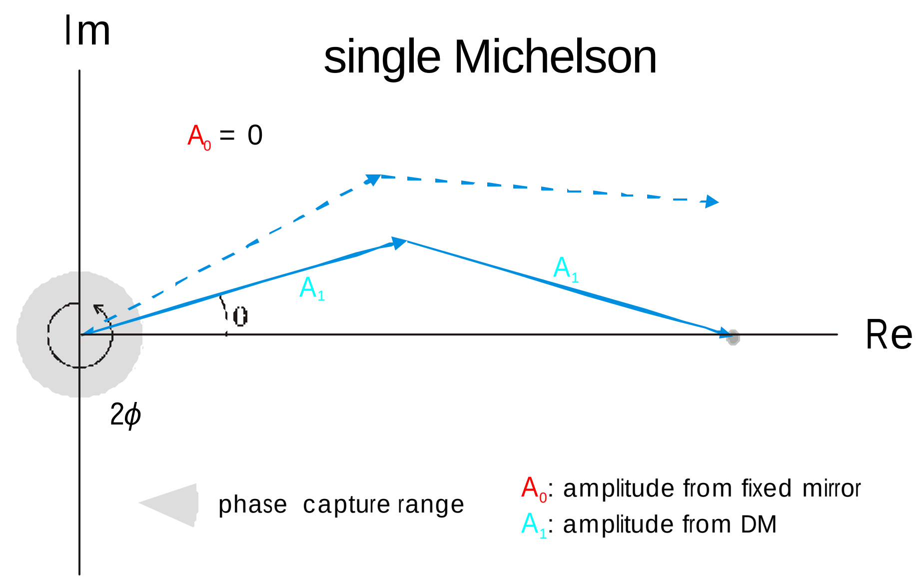
→ Increased phase capture range

asymmetric dual Michelson



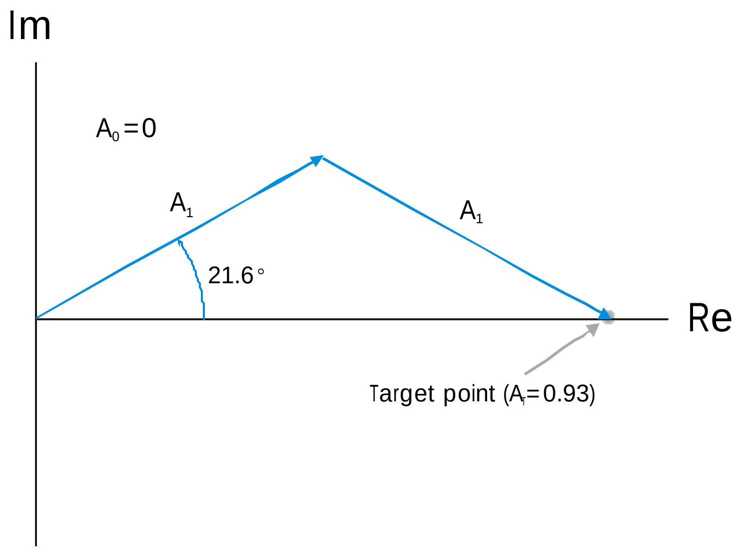
- resolution (phase & amplitude) can be high with a less accurate DM by adjusting the ratio of DM amplitude (A_1) to fixed mirror amplitude (A_0)
- phase capture range is limited by the relative amplitudes from the DMs (A_1) and the fixed mirror (A_0)

single Michelson



- resolution depends on the accuracy of the DM steps
- phase capture range can extend to a full 2π if DMs are capable of 0.5λ range of motion

Single Michelson Design: pre-TPF Requirements



Asymmetric dual Michelson system parameters:

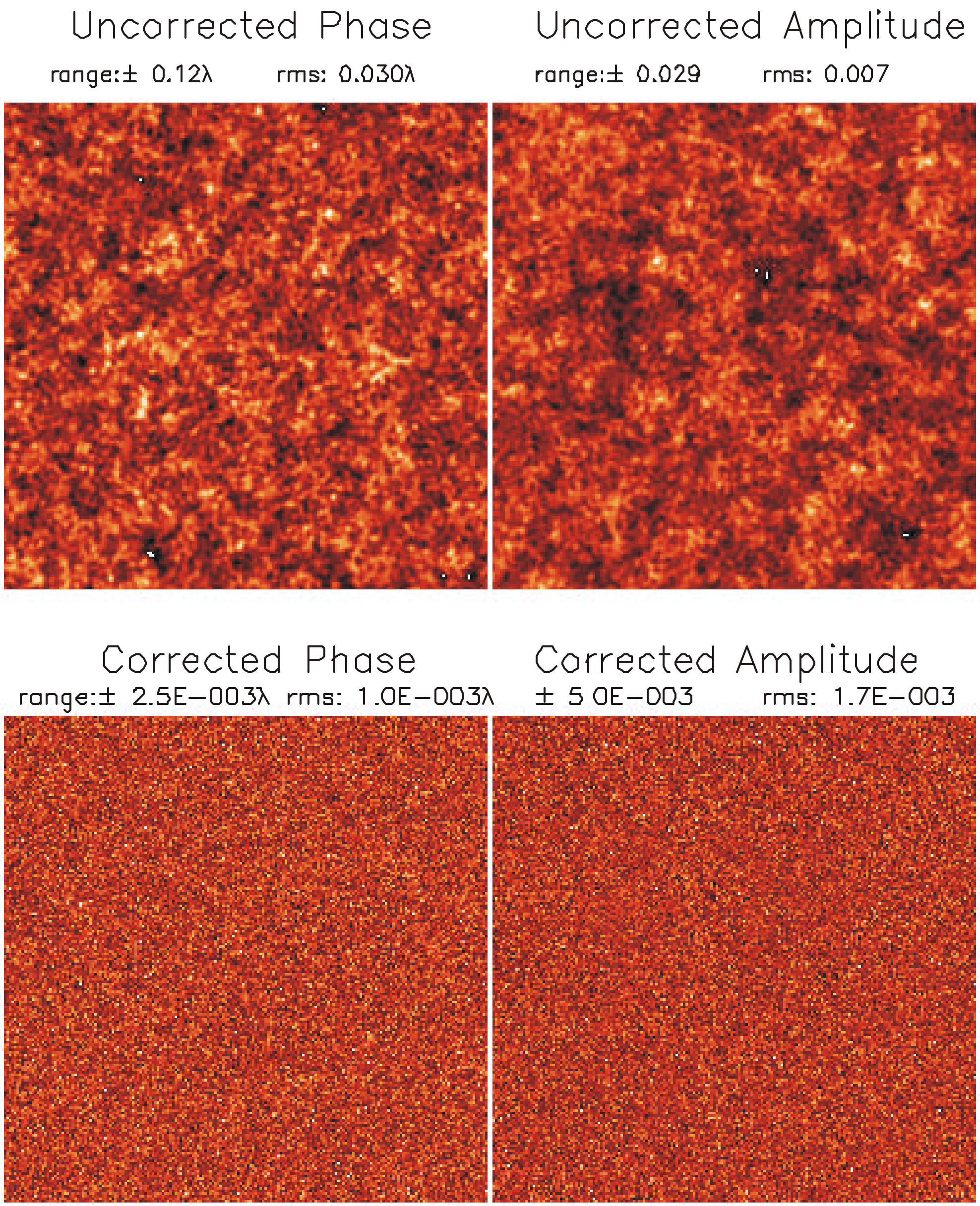
- DM step size: 1/400λ (1.5nm@ λ=600nm)
- BS1: absent BS2: R/T=0.50/0.50
  - A_0=0.
  - A_1=A_2=0.50
- Target point -
  - amplitude=0.93 (overall transmission=0.86)
  - phase=0.0
- Correction range limits
  - phase: ±0.5λ
  - amplitude: ±0.035

The goal of this design was to produce a pre-TPF system capable of producing 10^9 contrast, suitable for Jovian-like planet detection over the widest range of input phase errors and with a relatively coarse DM step. These conditions are appropriate where telescope phase errors and DM accuracy is not yet to TPF requirements but overall correction also does not have to be to TPF levels. To obtain a full 1λ phase capture range, we used a single Michelson system instead of a dual asymmetric system. DM step size accuracy needs to be only 1.5nm.

Coronagraph

- Lyot
- Gaussian soft stop, $T_{1/2}$ point at 4λ/D
- Lyot stop radius =0.72

Wavefront Correction: pre-TPF Example



The panels show the distribution of wavefront phase and amplitude non-uniformity for the uncorrected wavefront (upper panels) and following correction (lower panels).

Input Wavefront Error Distribution

Phase error distribution:

PSD ∝ $1/f^2$

bandwidth: 1-64 cycles/aperture

rms = 0.030λ (1/33 λ) range=±0.12λ

Amplitude error distribution:

PSD ∝$1/f^2$

bandwidth: 1-64 cycles/apertur

rms = 0.0070 range = ±0.029

Corrected Wavefront Error Distribution

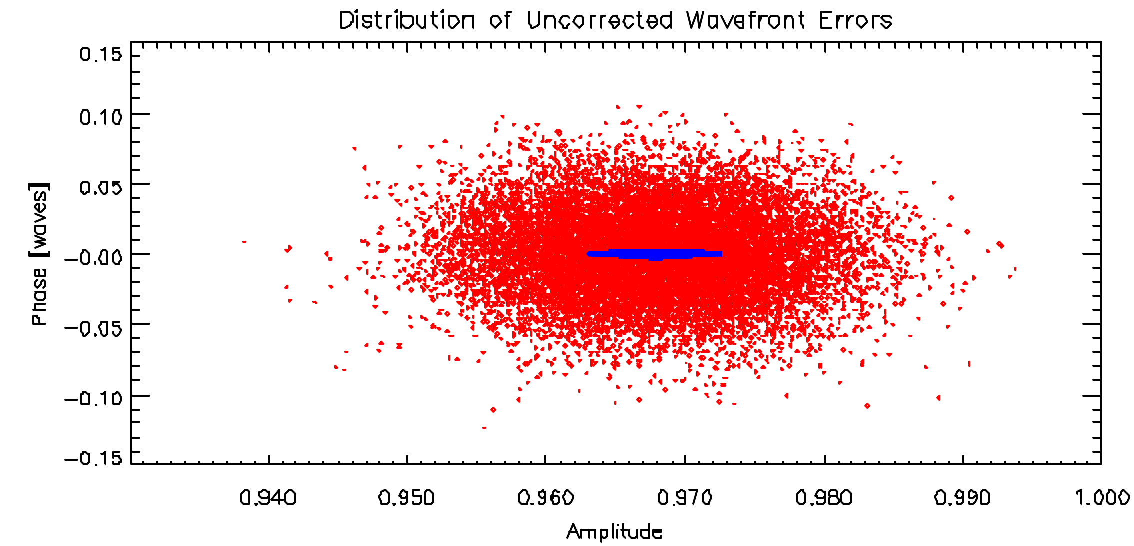
Phase errors:

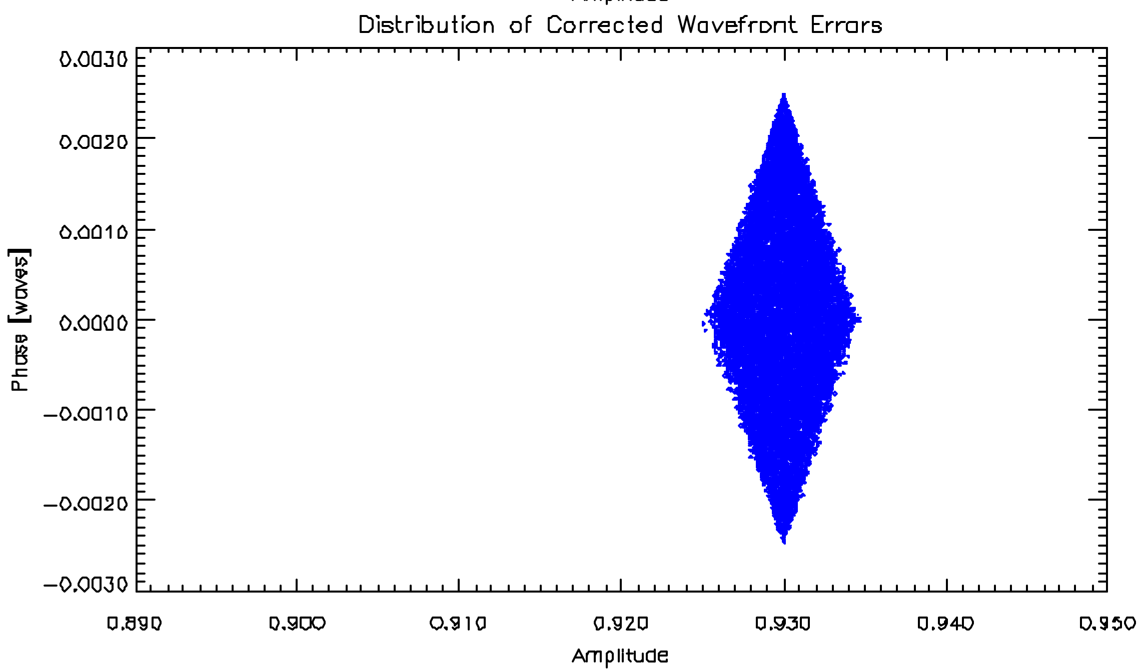
rms = 0.0010λ range = ± 0.0025λ

Amplitude errors:

rms = 0.0017 range = ±0.0050

Reduction of Wavefront Errors: pre-TPF Example





The distribution of WF errors before correction (upper panel) and following correction (lower panel) by the single Michelson system.

<u>Upper panel - uncorrected WF errors</u>

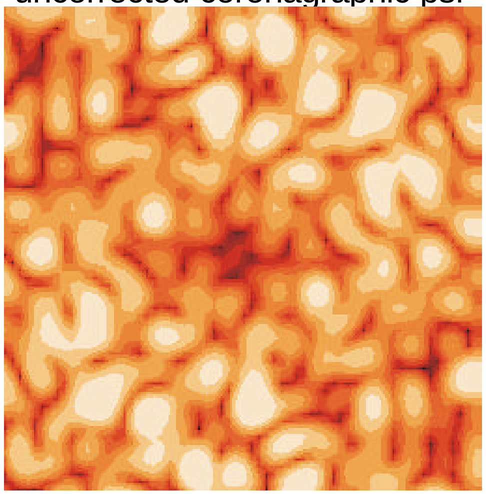
- Each point represents the uncorrected wavefront errors of phase (0.030l rms, ±0.12l range) and amplitude (0.007 rms, ±0.029 range).
- With the extended range of this system, all points in the beam have been corrected.
- The small, blue strip shows the residual WF errors following correction (amplitude value has been shifted to place both plots in the same range).

<u>Lower panel - residual WF errors following correction</u>

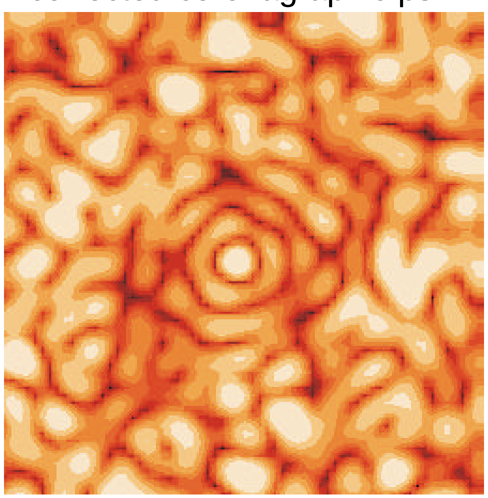
- Each point represents the corrected wavefront errors of phase (1.0×10^{-3}l rms, $\pm2.5\times10^{-3}$l range) and amplitude (0.0017 rms, ±0.0050 range).

Lyot Coronagraphic Performance: pre-TPF Example

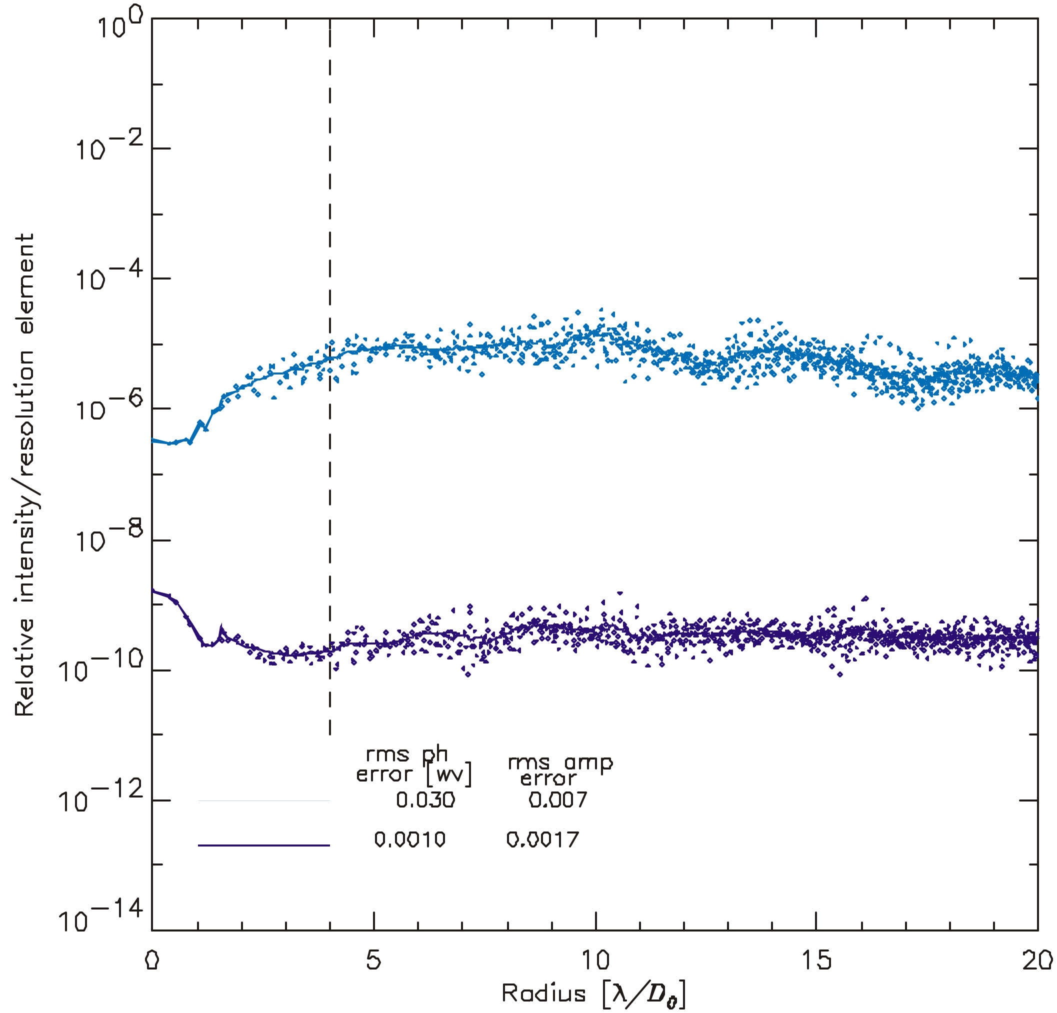
uncorrected coronagraphic psf



corrected coronagraphic psf

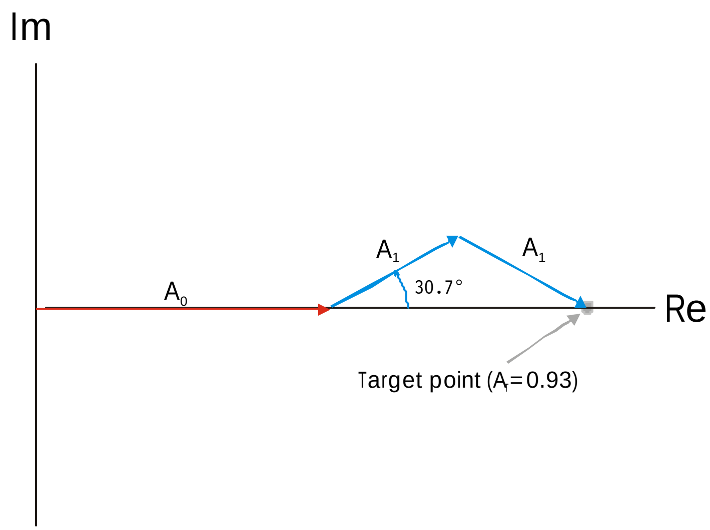


Images(log stretched) at the coronagraph output before (upper panel) and following (lower panel) correction with the single Michelson system.



Profiles of the coronagraphic output PSF without (upper curve) and with (lower curve) correction using the single Michelson system. The relative intensity/resolution element has been corrected by 4-5 orders of magnitude and now achieves the 10^{-9} level necessary for Jovian planet imagery.

Asymmetric dual Michelson Design: TPF Requirements



Asymmetric dual Michelson system parameters:

DM step size: 1/1200λ (0.5nm@ λ=600nm)

BS1: R/T=0.50/0.50, BS2: R/T=0.50/0.50

A_0=0.50

A_1=A_2=0.25

Target point -

amplitude=0.93   (overall transmission=0.86)

phase=0.0

Correction range limits:

phase: ±0.060λ

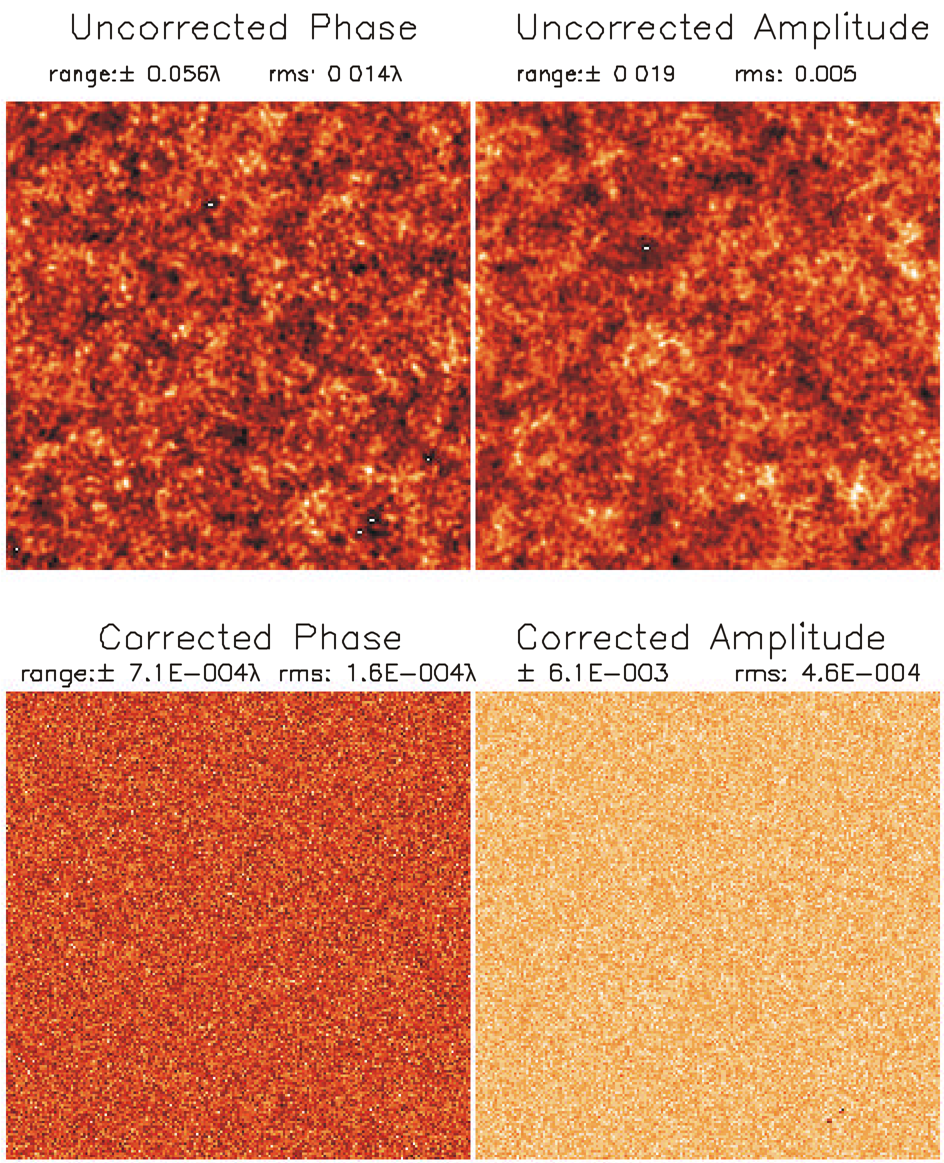
amplitude: ±0.035

This design compensates for relatively large range of phase (0.014λ = 1/70λ rms) and amplitude errors (0.005 rms) to achieve TPF requirements for contrast. The asymmetric aspect has been reduced to allow compensation for the full phase error range; the DM step size is 1/1200λ or 0.5nm at λ=600nm. Should the necessary input phase range be reduced, adjustment of the reflectivity and transmission of beamsplitter 1 can be made to further lessen the requirements on DM step size.

Coronagraph

- Lyot
- Gaussian soft stop, $T_{1/2}$ point at 4λ/D
- Lyot stop radius =0.72

Wavefront Correction: TPF Example



The panels show the distribution of wavefront phase and amplitude non-uniformity for the uncorrected wavefront (upper panels) and following correction (lower panels).

<u>Uncorrected Wavefront Error Distribution</u>

Phase error distribution:

PSD $\propto 1/f^2$

bandwidth: 1-64 cycles/aperture

rms = 0.014λ (1/71λ) range = ±0.056λ

Amplitude error distribution:

PSD $\propto 1/f^2$

bandwidth: 1-64 cycles/aperture

rms = 0.005 range=±0.019

<u>Corrected Wavefront Error Distribution</u>

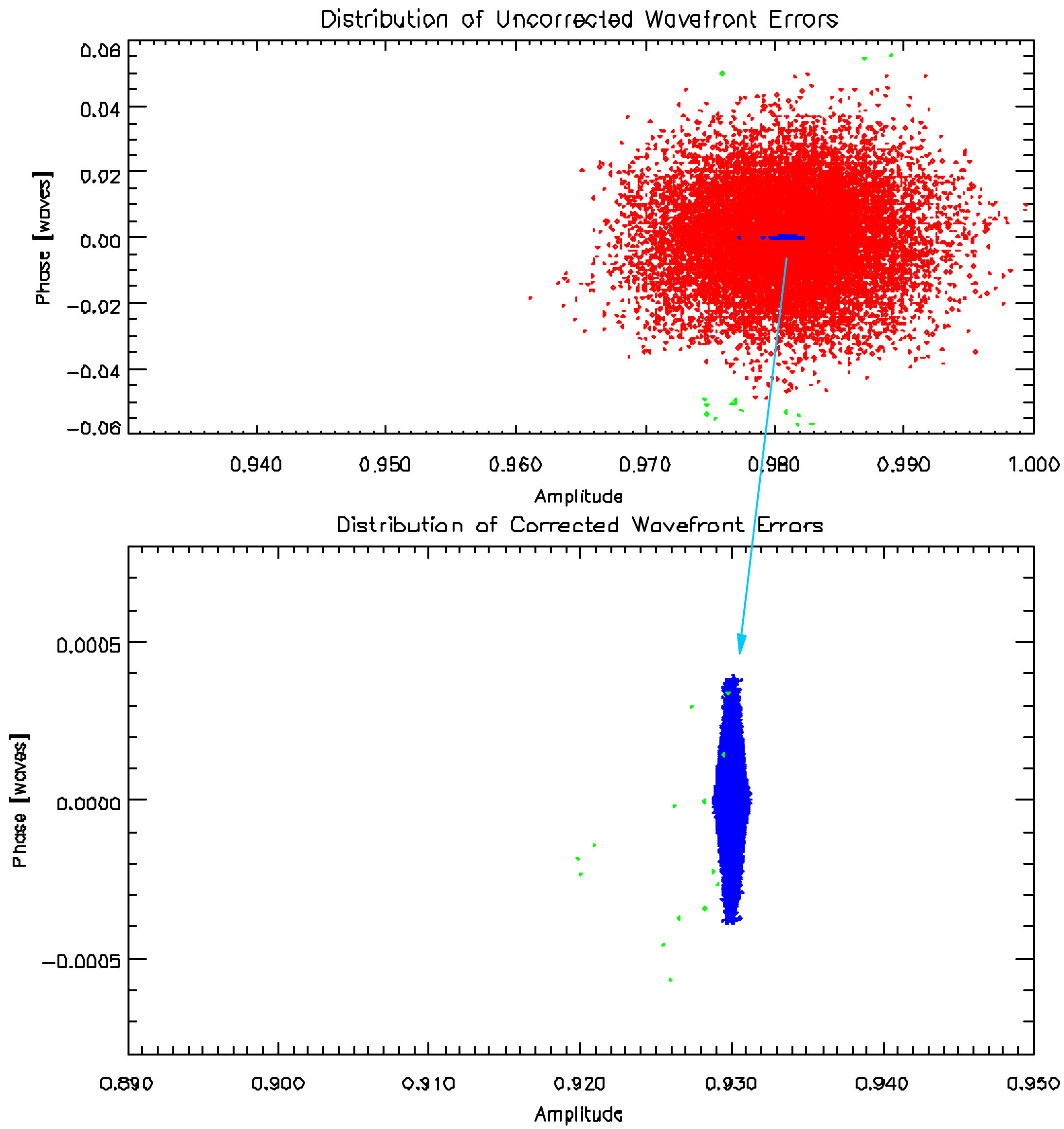
Phase errors:

rms = $1.6\times10^{-4}\lambda$ range = $\pm 7.1\times10^{-4}\lambda$

Amplitude errors:

rms = 4.6×10^{-4} range =$\pm\ 6.1\times10^{-3}$

Reduction of Wavefront Errors: TPF Example



The distribution of WF errors before correction (upper panel) and following correction (lower panel) by the asymmetric dual Michelson system.

Upper panel - uncorrected WF errors

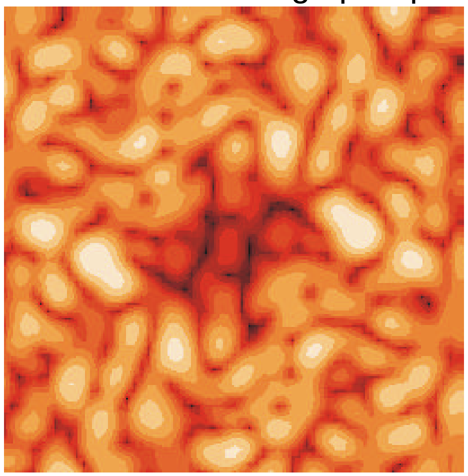
- Each point represents the uncorrected wavefront errors of phase (0.014l rms, ±0.056l range) and amplitude (0.5% rms, ±1.9% range).
- The green symbols show those points on the WF which lay outside the correction range and so had incomplete (though still very good) correction.
- The small, blue strip shows the residual WF errors following correction (amplitude value has been shifted to place both plots in the same range).

Lower panel - residual WF errors following correction

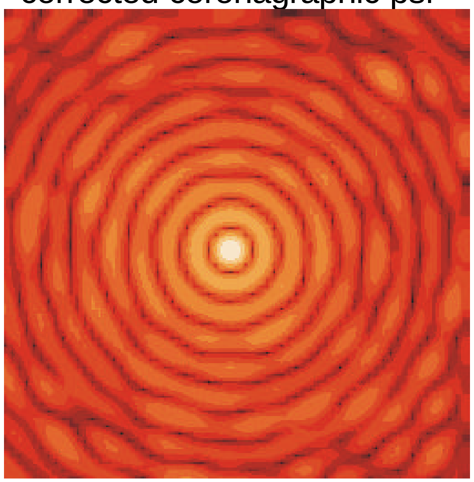
- Each point represents the corrected wavefront errors of phase (1.6x10^{-4}l rms, ±7.1x10^{-4}l range) and amplitude (4.6x10^{-4}rms, ±6.1x10^{-3} range).
- The green symbols show the characteristic distribution of residual phase and amplitude errors which were outside the range for complete correction. The effect of a small number of such points has a negligible effect on the final coronagraph performance.

Lyot Coronagraphic Performance: TPF Example

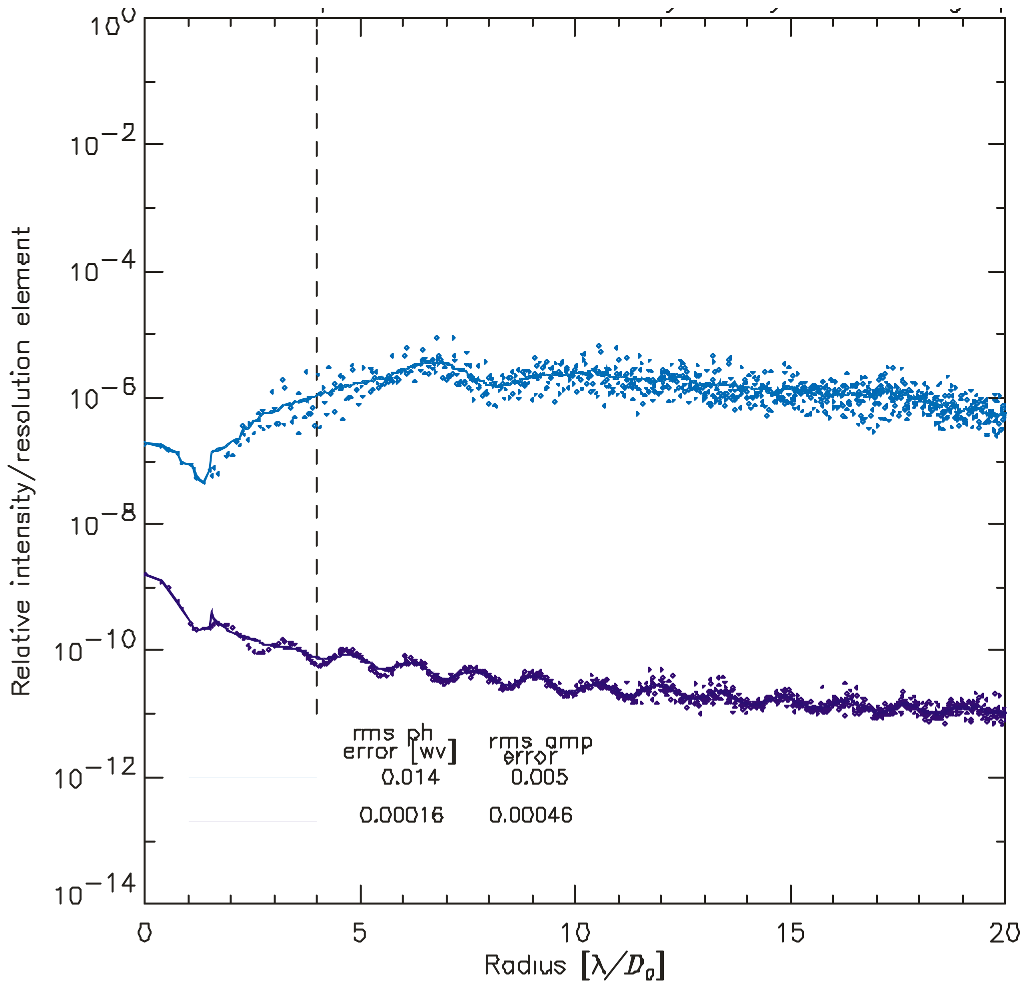
uncorrected coronagraphic psf



corrected coronagraphic psf



Images(log stretched) at the coronagraph output before (upper panel) and following (lower panel) correction with the asymmetric dual Michelson system.



Profiles of the coronagraphic output PSF without (upper curve) and with (lower curve) correction using the asymmetric dual Michelson system. The relative intensity/resolution element has been corrected by 4-5 orders of magnitude and now achieves the 10^{-10} level necessary for terrestrial planet imagery.